Laser-induced dynamics of liquid tin microdroplets

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Chapter 1

Introduction

Micro-electronic devices are the core of many tools we use in our everyday life. Their performance has been pushed by the semiconductor industry over past decades since the invention of the transistor (Nobel Prize for Shockley, Bardeen and Brattain in 1956) and its development into an integrated circuit (Nobel Prize for Alferov, Kroemer and Kilby in 2000). The development of shrinking the sizes of electronic elements leading to ever denser packing of integrated circuitry led Gordon Moore, founder of Intel company, in 1965 to the observation and prediction that the number of transistors on a microelectronic chip doubles every year [1]. This is represented in Fig. 1.1(left). In 1975 the statement was revised to a doubling every two years [2].

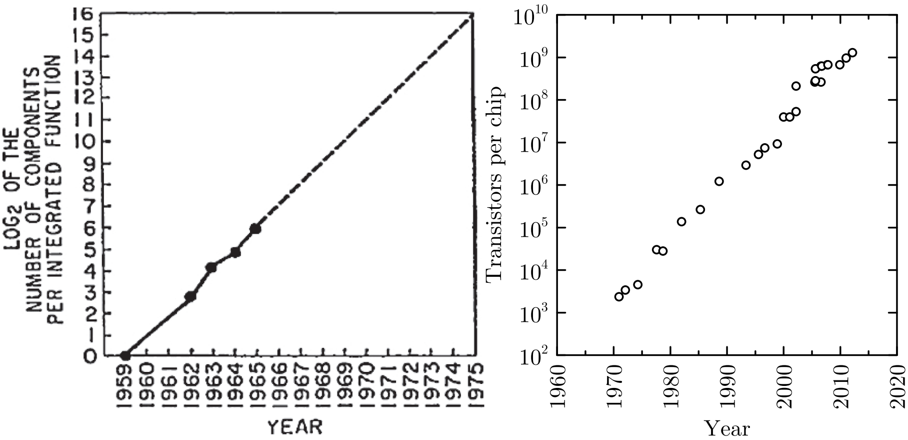

FIGURE 1.1: A trend of the amount of components per integrated circuit (left) predicted by G. Moore in 1965 (reprinted from Ref. [1]) and (right) as observed over the past five decades (adapted from Ref. [3]).

Moore's prediction that this rapid development would sustain at the same pace over years to come has become known as Moore's law. This empirical law evolved from a prediction to a driving principle for the chip-manufacturing industry, and eventually even to a roadmap, the International Technology Roadmap for Semiconductors, with participation of industry associations on three different continents [3, 4]. Indeed, as is shown in Fig. 1.1(right) Moore's law has been kept alive over the past five decades [3, 5]. A sustained increase of the density of elements on computer chips remains a challenge to industry and ignites technologies and scientific developments beyond the state-of-the-art.

One of the crucial processes underlying this trend is photolithography [6, 7]. It is a photochemical process where a coated silicon wafer covered with a layer of photoresist is exposed to light through a mask with a specific structure [8]. This structure corresponds to a future circuit on a layer of a semiconductor chip. After the exposure and subsequent development, the photoresist forms a planar structure that leaves only a certain area on the wafer exposed to the next steps, such as etching, ion implantation, and deposition. In this chain of repetitive manufacturing steps (see Fig. 1.2) photolithography plays a key role by ensuring the transfer of desired structures on the nanometer scale. The Critical Dimension (CD), or resolution, is the minimum feature size that can be printed in the photoresist. It is conventionally written as:

$$\mathrm{CD} = k_1 \times \frac{\lambda}{\mathrm{NA}}. \tag{1.1}$$

Here, k_1, typically 0.3–0.4, is a parameter that depends on the characteristics of a specific lithography process, such as the photoresist, type of the mask and its pattern; λ is the wavelength of the exposing light, and NA is the numerical aperture of the exposure tool. Steady progress in shrinking the minimum size

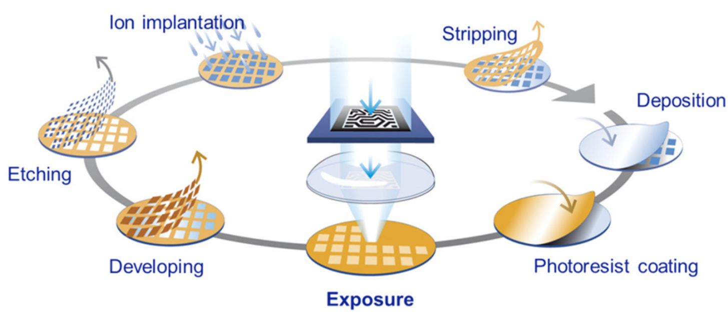

FIGURE 1.2: Main manufacturing steps of a semiconductor device (reproduced from Ref. [9]).

of the elements on a chip is supported by improvement of all three parameters. The wavelength went through several steps of reduction: 365 nm, 248 nm, 193 nm, and, the most recent one, 13.5 nm [10]. The photolithography process and the chemical species of the photoresist depend on the wavelength of the light chosen to expose the wafer. For each system with a specific wavelength, the numerical aperture experienced several improvement steps as well. For example, for the 193-nm-wavelength systems, the latest big step was made by introducing the immersion technique with NA>1, which made it possible to produce modern chips with feature sizes down to 10 nm.

EUV lithography

After over 20 years of research and development, lithography in the extreme-ultraviolet wavelength range (EUVL) is now being used by the main semiconductor manufacturers [11]. In 2018, EUVL became possible for high-volume manufacturing (HVM) after passing the threshold of EUV light source power of 250 Watts [12]. State-of-the-art sources of extreme-ultraviolet light employ tin plasma as an emitting medium in which a certain charge state population is reached by interaction with a high-intensity 10-μm-wavelength pulse from a CO_2 laser [13]. The produced light with a spectral peak at 13.5 nm is collected and transferred by means of Mo/Si multilayer mirrors. Due to their limited reflectance (max $\sim 70\%$) and a small bandwidth ($\pm 1\%$), only a small fraction of the produced light can be effectively used for lithography. After bouncing from several mirrors that are needed to image and demagnify the pattern of the mask (reticle), the intensity of the EUV radiation drops significantly before it reaches the photoresist layer on the wafer. A continuous demand for ever more powerful light sources provides an ongoing challenge to industry as well as to the scientific community. Profound understanding of the atomic plasma processes during the laser-matter interaction is crucial to increase the conversion efficiency (CE) of the drive laser energy into EUV radiation in the aforementioned “in-band” 2% bandwidth around 13.5 nm.

Another challenge is the lifetime of the source, which is affected by many parameters, but primarily by the degradation of the first mirror. This first, “collector” mirror focuses the in-band EUV light that is emitted in the laser-facing hemisphere, to the other optic elements inside the lithography tool. Its location in the vicinity of the plasma could potentially result in very fast contamination caused by both neutral and charged particles (debris) originating from the laser-matter interaction [13–16]. A continuous flow of hydrogen gas is directed inside the vessel in order to capture the high influx of tin debris. By exchanging the momentum in multiple collisions with energetic tin ions, the hydrogen molecules slow down the ionic debris and redirect it toward the vacuum exhaust. Hydrogen was chosen as a compromise between low stopping power per particle (in view of its low atomic mass) and the high transmissivity for EUV light. Moreover, hydrogen radicals formed near the primary plasma can etch away any tin deposited on the collector mirror, forming a stannane gas (SnH_4) that should also be removed from the collector mirror before its dissociation. Another approach, a magnetic guidance technique has also shown its benefit in redirecting high-energy tin ions from the mirror. However, this requires high magnetic fields and a hydrogen flow is still needed for debris mitigation [17].

In case of laser interaction with a solid tin target, a significant amount of tin is ejected as debris particles harmful for the source performance [17, 18]. Therefore, to reduce contamination of the EUV source, several other geometries for tin targets were explored, delivering reduced amounts of redundant “fuel”. Target concepts as sprays, rotating cylinders or disks, and tin jets were tested [19]. However, it was shown that the most practical way of delivering tin is in the form of mass-limited spherical microdroplet targets. Limiting the available tin mass interacting with the laser pulse by providing the tin in small, isolated droplets results in a significant reduction of debris inside the source vessel.

For a stable and efficient interaction with the laser pulse the droplets, obtained by a controlled coalescence of small droplets originating from a breakup of a liquid tin jet, should be produced with reproducible temporal and spatial characteristics. Moreover, the laser-droplet interaction event can affect the shape and position of the subsequent droplet, which in turn may result in a reduction of the produced EUV light. It was found that the droplet stream should have a large velocity ($\sim$100 m/s) in order to ensure high power operation at the required high, 50-kHz repetition rate [18]. All these requirements have significant impact on the design of the EUV source.

The high-power CO_2 lasers that were chosen to drive the tin plasma in EUV light sources have a wavelength of 10.6 μm. The main reasons for that were high conversion efficiency of the laser light of this wavelength into the desired 13.5($\pm$1%) nm, and availability of such high-power laser for industrial applications. To provide an optimum coupling between the drive laser light and the tin mass, the spherical liquid droplet is typically first deformed into some suitable target shape. For this purpose, in current industrial systems a separate pulse, a so called “pre-pulse” is used [18] (see Fig. 1.3). This pulse, with a duration of a few tens of nanoseconds at an intensity sufficient to ablate a small fraction of the tin droplet ($\sim$1%), is capable of producing tin plasma on the laser-facing side of the droplet. Formed within the duration of the laser pulse, this plasma eventually expands, giving a rise to a pressure kick to the remaining part of the droplet [20–22]. Such an impact expands the droplet and accelerates its center-of-mass away from the laser interaction zone. By choosing the appropriate laser intensity, the droplet can be expanded into a thin disk-like shape that in a couple of microseconds after

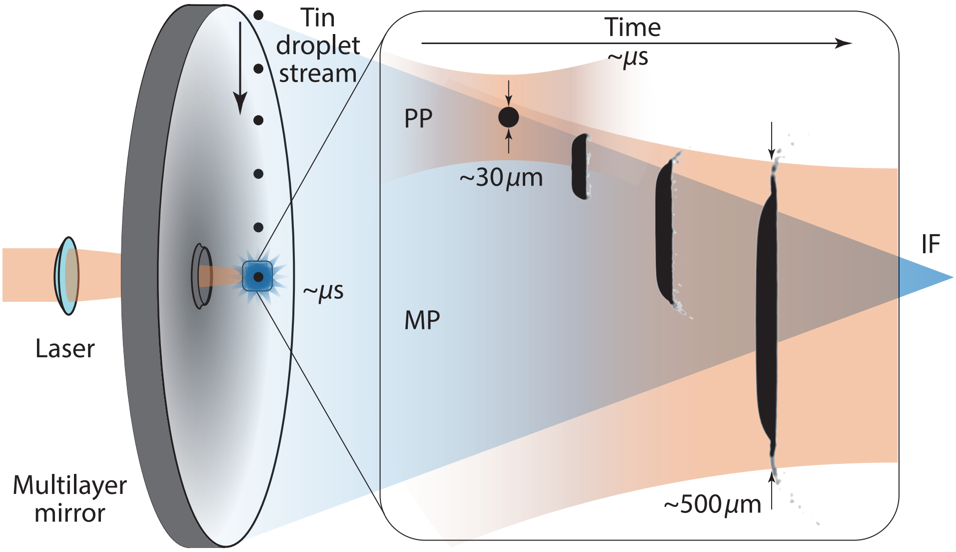

FIGURE 1.3: Simplified schematics of the laser-droplet interaction in EUV light sources. A spherical microdroplet hit by a laser pre-pulse (PP). The droplet is propelled and reshaped into a (tilted) disk target suitable for the main-pulse laser irradiation (MP). Highly-ionized, EUV emitting tin plasma is created as a result of the high energy main-pulse laser impact. A multilayer mirror (left) collects the light emitted in the laser-facing hemisphere ($\sim 2\pi$ solid angle) and focuses it at the intermediate focus (IF).

the pre-pulse matches the beam size of the second, main laser pulse ($\sim$500 μm). The main pulse carries intensity ($\sim 10^{11}$ W/cm^2) that is optimal for producing ion charge states of tin that efficiently contribute to the light emission around 13.5 nm (Sn^{8+}–Sn^{14+}) [23].

The EUV sources currently used by the semiconductor manufacturers utilize pre-pulses of 10-μm wavelength and duration of several tens of nanoseconds produced by the same CO_2 laser system that produces main pulses. More than 20 kW of the input laser power is needed to produce EUV light at the level for HVM [18]. Therefore, the industry considers using separate, more efficient laser systems for pre-pulse, thus leaving all CO_2-laser power for EUV generation. One of the possible substitutes is a solid-state laser system emitting light at 1-μm wavelength. Due to the shorter wavelength, the ablation of tin droplets is more efficient. There are several other advantages of using separate laser system for pre-pulses, such as separate beam paths, meaning better light isolation between pre-pulse and main pulse, and the capability of a simplified spatial and temporal shaping. Moreover, it becomes possible to use a different pulse duration.

Recent developments [17, 18] produced tentative evidence for improved source performance when replacing the ns-pre-pulse with a ps-pulse laser. The physics dramatically changes switching from nanosecond to these picosecond laser pre-pulses. Such very short laser pulses can produce strong shock waves that propagate in the tin droplet, and focus right in the center of the droplet, where they lead to explosive cavitation and spallation with absolutely spectacular results [24–30]. Such volumetric, finely dispersed target shapes are expected to be able to provide benefits regarding main pulse absorptivity and EUV emissivity when compared to the disk-type shapes created by nanosecond laser pulses.

This broad scope of pre-pulse physics, with the aim of producing suitable target shapes in tin microdroplet-based laser-driven plasma sources, provides an ideal environment for combining industrial innovations with attractive scientific questions that range from the physics of dense plasma to fluid dynamic deformations.

Thesis outline and summary

This work aims to advance the understanding of the underlying physics of the laser target formation in state-of-the-art and future laser-produced plasma sources of EUV light. An experimental setup, an EUV light source based on tin droplets was constructed at ARCNL to perform studies under industrially relevant conditions as found in next-generation EUV lithography machines. It utilizes both commercial and home-built solid-state laser systems to perform high-resolution measurements of the fluid and plasma dynamics governing the target formation. The detailed description of the setup is provided in Chapter 2 of this thesis.

In Chapter 3, the first experimental results are presented as obtained with the setup, discussing the dynamics of tin microdroplets as a result of an ablative impact of 10-ns 1-μm laser pulses visualized by short-pulse stroboscopic shadowgraphy imaging tools. The droplet propulsion is captured in a scaling law of the plasma-imparted momentum over three decades in laser energy. The fluid-dynamic response is described by an analytical model that also shows scalability of our results with the results from the water-droplet experiments carried out at the University of Twente [31]. These findings enable optimization of the laser-droplet coupling important for reaching high CE in EUV sources.

Further, Chapter 4 provides a more detailed insight in the plasma physics underlying the plasma propulsion of the droplet, combining an extensive set of experimental results with results of radiation-hydrodynamic simulations with the RALEF-2D code [32, 33]. Good agreement was found between the experiment and simulation for the majority of the explored laser energies, revealing a scaling law of the plasma-propulsion velocity of droplets with laser energy. Further, we perform a careful examination of the underlying physics trying to derive the obtained scaling from the existing analytical theories and conclude that none of them can be directly applied to our system.

The efficient operation of an EUV source highly depends on the stability and reproducibility of the produced laser targets. Combining an analytical modeling of the plasma pressure impact on a spherical droplet with experimental observations, Chapter 5 discusses the sensitivity of the target tilt angle, propulsion and expansion to the alignment of the laser beam with respect to the droplet. Then, our validated model is used to predict sensitivities for several practical cases directly relevant for current industrial EUV light sources.

In Chapter 6, the results from two different experimental systems, with millimeter-sized methyl ethyl ketone droplets (performed in the Physics of Fluids group at the University of Twente) and tin microdroplets (performed in the EUV Plasma Processes group ARCNL) are used in a complementary manner to understand in detail the fragmentation of laser-impacted liquid droplets.

The impact of shorter laser pulses, 15 ps in duration, that results in cavitation-driven expansion of tin microdroplets is discussed in Chapter 7. This type of target is shown to be beneficial for EUV generation in some cases but still requires further investigation of its dynamics. Combining an experimental approach with an analytical description, the observed tin mass distributions obtained from droplets of two different sizes are shown to be governed by a single dimensionless parameter, the Weber number. A summary phase diagram (target size—laser energy) is provided, capturing different behavior of the expanding tin droplets that depends on the imparted laser energy.

The results obtained in this thesis enable a more thorough understanding of physics underlying two main prepulse approaches and pave the way for even more comprehensive studies of the final-state mass and velocity distributions after fragmentation of the target material.